文章编号: 1001－2060(2004)03－0256－04

循环流化床中石油焦与煤混合燃烧温度场研究

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摘　要: 石油焦是炼油工艺的副产品, 具有低灰分、一定挥发份和高热值的特性。焦中含有相当多的硫、氮元素和钒、镍等碱金属元素, 这些成分在石油焦燃烧时可造成锅炉内腐蚀和沾污。经过技术对比认为: 利用循环流化床燃烧技术将石油焦与煤混合燃烧是高效、清洁回收利用石油焦的有效方法。本文在热输入率为 0.5 MW 的循环流化床热态试验装置上进行了石油焦与煤掺混燃烧炉内温度场研究, 分析了石油焦与煤不同燃料配比, 不同锅炉运行参数, 如一次风率、过量空气系数、Ca/S 比和给料量等对炉内温度场分布的影响规律。

关　键　词: 循环流化床; 石油焦; 煤; 混烧; 温度场

中图分类号: TQ038.1　　文献标识码: A

1　前　言

石油焦是炼油工艺的副产品, 灰分很低, 有一定挥发份, 具有高热值的固体燃料。由于其成分里含有相当多的硫、氮元素和钒、镍等碱金属元素, 是造成腐蚀、沾污等的主要原因; 另外其着火和燃烧也较困难, 所以石油焦属于劣质燃料[1~2]。基于燃烧和污染物排放方面考虑, 作者认为利用循环流化床技术, 石油焦与煤混烧是高效、清洁利用石油焦的有效方法。循环流化床锅炉的特点是低温动力控制燃烧和高强度的热量、质量和动量传递过程, 使整个炉膛高度的温度分布均匀。因而循环流化床锅炉燃烧时, 炉内温度场分布是至关重要的, 它可反映出炉内气固流动特性、燃烧特性和热量传递特性等。本文在 0.5MW 循环流化床热态试验台上进行了石油焦与煤混合燃烧试验, 研究了焦煤比和锅炉运行参数等对炉内温度场分布的影响规律。

2　燃料特性

试验所选用的燃料为金陵石化热电厂所用的煤和石油焦。燃料的元素分析和工业分析数据如表 1～表 2 所示。从表中可看出, 石油焦是富含碳的燃料, 碳含量高达 87.01%, 低位发热量为 33.85 MJ/kg, 灰分很少, 与煤相比, 硫、氮的含量较高。燃料的粒度分析结果如表 3 所示, 煤的平均粒径约为 2.508 mm, 石油焦的平均粒径约为 1.413 mm。石油焦与煤相比, 粒径偏细, 这是由于石油焦常温可磨系数 (Hardgrove) 约为 73.6, 属易破碎和磨细燃料。在燃烧过程中, 燃料越细, 更应控制运行参数, 防止机械不完全燃烧热损失。

表 1　燃料的元素分析

燃料	元素分析(收到基)/%				
	Car	Har	Oar	Nar	Sar
煤	58.98	2.9	9.39	0.86	0.76
石油焦	87.01	3.68	2.22	2.18	1.88

表 2　燃料的工业分析

燃料	工业分析(收到基)/%				发热量(收到基)/MJ·kg⁻¹	
	全水 M_{tol}	灰分 A_{ar}	挥发份 V_{ar}	固定碳 C_{fix}	低位发热量 Q_{dw}^{y}	高位发热量 Q_{gw}^{y}
煤	6.1	21.02	23.61	49.27	22.42	23.16
石油焦	2.4	0.63	13.53	83.44	33.85	34.67

表 3　燃料的粒度分析

燃料	各粒径重量份额/%								平均粒径/mm
	<0.16 mm	0.16~0.315 mm	0.315~0.63 mm	0.63~1.25 mm	1.25~2.5 mm	2.5~5 mm	5~6 mm	>6 mm	
煤	19.9	3.6	13.7	14.9	7.3	20.9	3.8	15.9	2.508
石油焦	20	4.7	19	21.6	10.4	20.9	3.4	0	1.413

3　试验装置[3]

试验装置为东南大学热能工程研究所自行设计、建造的循环流化床热态试验台, 流程如图 1 所示。试验台配备有完整的压力、温度和流量测量装置; 预留有固体和烟气取样口, 在试验过程中, 能实时地进行固体和烟气取样[1~2]。此试验台热输入率

收稿日期: 2003－07－15;　修订日期: 2003－09－15
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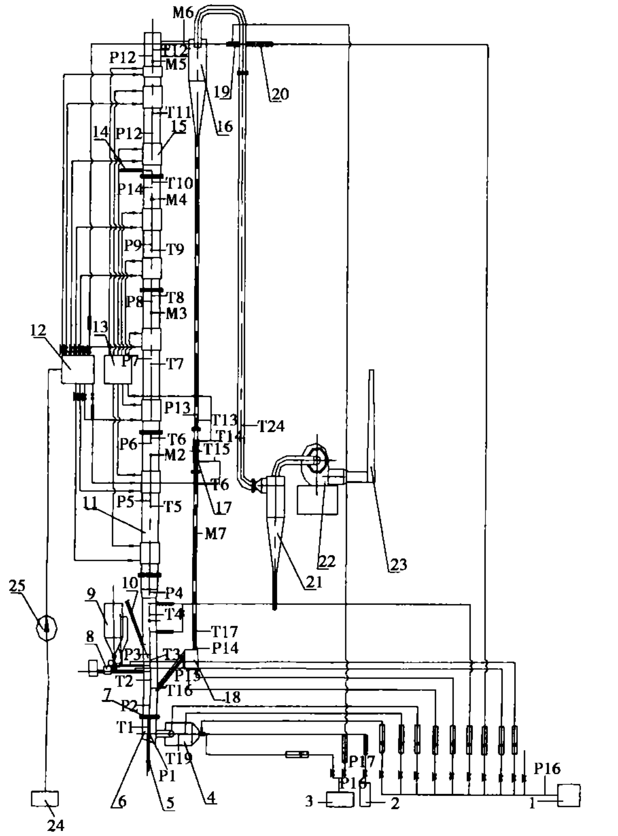
为 0.5 MW, 炉膛密相区内径为 300 mm, 内敷有 50 mm 厚的耐磨材料, 稀相区内径为 400 mm。炉膛总高 12 m。



1-罗兹风机 2-油泵 3-空气压缩机 4-启动燃烧室 5-排渣管 6-风室 7-布风板 8-螺旋给料器 9-料斗 10-下料管 11-炉膛 12-进水联箱 13-出水联箱 14-后燃系统 15-水夹套受热面 16-旋风分离器 17-循环物料测量仪 18-返料器 19-水冷却系统 20-风冷却系统 21-旋风除尘器 22-引风机 23-烟囱 24-水池 25-水泵 T1~T20:温度测点 P1~P18:压力测点 M1~M7:固体和气体取样点

图 1　CFBC 热态试验装置系统图

4　试验结果及分析

4.1　一次风率对温度场的影响

图 2 为一次风率对温度场的影响曲线。可看出, 对于不同掺混比燃料, 总的趋势是随一次风率增大, 密相区温度降低, 炉膛温度更趋于均匀。不同掺混比燃料, 其燃料成分和粒度都不同, 则一次风率变化对其燃烧的影响程度也不尽相同。对于纯焦燃烧, 密、稀相区温差很大, 燃烧份额分布、燃烧组织都不理想。

一次风率对炉内温度场的影响可从燃烧份额分布及烟气携带热量等方面分析。当一次风率增加, 氧气供应量增加, 密相区的燃烧份额有所上升, 但受密相区气泡相和乳化相之间传质阻力的限制, 燃烧份额并未按同等比例增加。另外, 一次风率增大, 密相区气泡变大, 气泡上浮速度加快, 从而使更多的燃料颗粒被夹带、扬析进入稀相区, 使密相区燃烧份额减小, 稀相区燃烧份额增大。还有, 一次风率增大, 在相同温度下密相区烟气携带热量增多。一次风率对温度的影响, 是这两方面综合作用的结果。对不同燃料、不同运行工况, 这两方面的作用是不同的, 导致一次风率对温度场的影响也不一样。对于大颗粒、高挥发份的燃料, 增大一次风率, 密相区燃烧份额增大, 温度升高。对于本试验所用石油焦, 是细粒、低挥发份燃料, 增大一次风率, 使气泡的产生越多, 生长越大, 气体就越难穿过由细颗粒组成的乳化相; 而气泡的上浮速度越快, 增加了气泡的破裂强

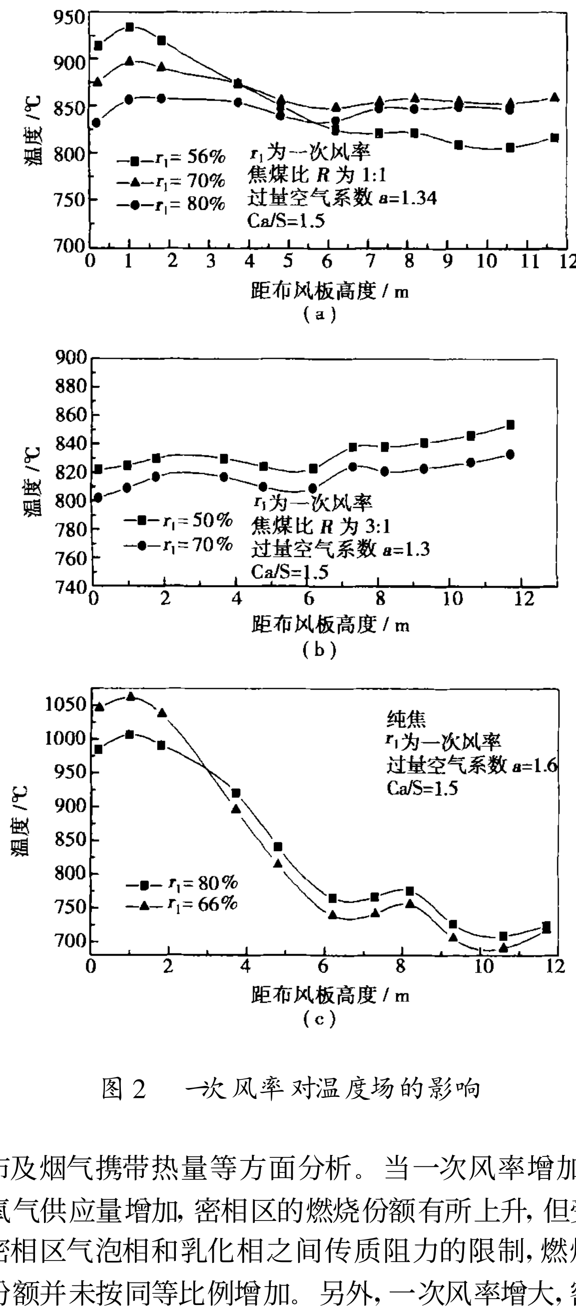


图 2　一次风率对温度场的影响

度，增大了密相区向稀相区的物料扬析量，从而密相区温度降低。

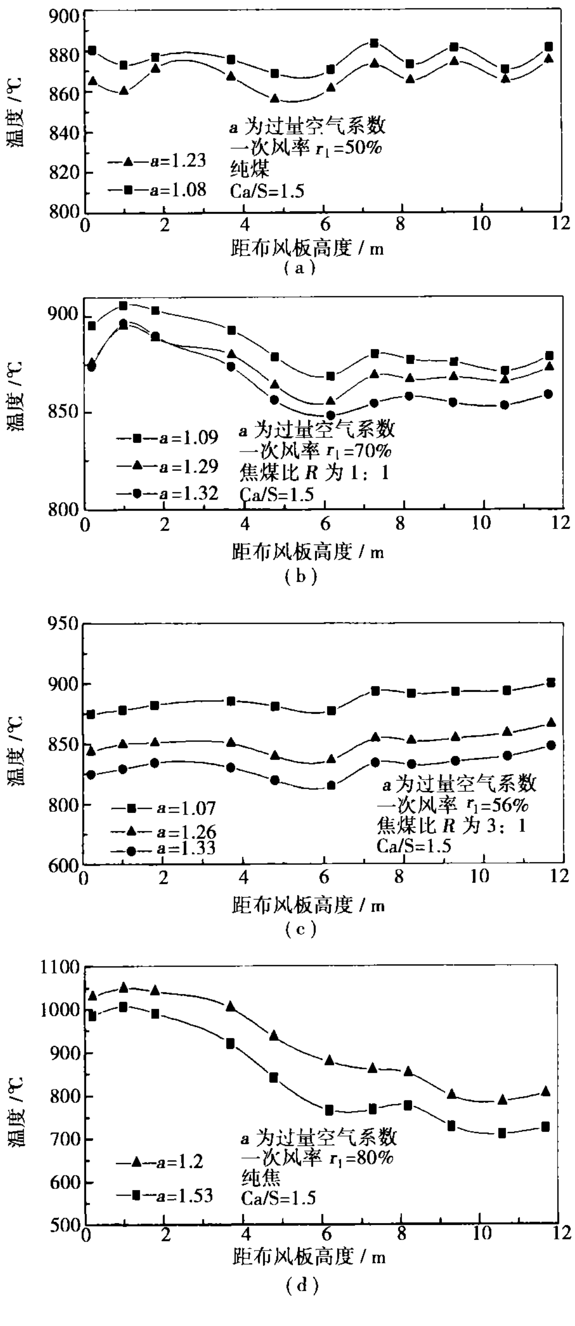


图 3 过量空气系数对温度场的影响

对于纯石油焦燃烧而言，其密、稀相区温差很大，这与石油焦灰分低、热值高的燃料特性有关。在无外加床料情况下，石油焦燃烧形成不了高浓度、高通量的物料循环。密相区热量无法通过高浓度循环量带入稀相区，所以密、稀相区温差大。当循环流化床纯燃石油焦时，必须在燃料中加入惰性床料，或与其它燃料混烧，才更易控制石油焦在炉内的燃烧。

4.2 过量空气系数对温度场的影响

过量空气系数对炉内温度场的影响如图 3 所示。对不同掺混比燃料，随过量空气系数增大，密、稀相区的温度均降低。这是由于随着过量空气系数增大，炉膛内流化速度增大，物料循环量增大，烟气与受热面间的传热系数增大，受热面吸热量增多，炉内温度降低。过量空气系数增大，炉膛出口烟气热损失增大也会导致炉内温度降低。

4.3 Ca/S 摩尔比对温度场的影响

图 4 为 Ca/S 比对炉内温度场的影响曲线。燃料为焦煤比为 1∶1 的混合燃料。当一次风率为 70％时，随 Ca/S 比增大，密、稀相区温度都降低。Ca/S 比从 1.5 升到 2.5 后，炉内平均温度由约 880 ℃降为约 820 ℃；但当一次风率为 55％时，随 Ca/S 比增大，密相区温度降低，而稀相区温度则升高。

石灰石投入炉内后，将发生复杂的物理、化学过程，对床温影响较大。常温下的石灰石进入炉膛后，在床料的热交换下，温度升高到床层温度，此过程吸收物理热。石灰石温度继续升高到一定温度后发生煅烧反应，吸收热量，反应热为：183 kJ/mol。煅烧后的生石灰与烟气中的 SO_2 发生固硫反应，放出热量，反应热为：500 kJ/mol。在保证一定脱硫效率的情况下，当 Ca/S 比增大，石灰石煅烧反应吸热量增加，床温降低。

浙江镇海炼化公司有两台 220 t/h 纯烧石油焦的循环流化床锅炉，2 号炉出现了与设计值相比床温偏低现象，表 4 为其运行参数表。为此，采取了一些相应措施：减少石灰石给料量由 2 t/h 降至 0.6 t/h；减少一次风量，增加二次风量；减少排渣量等，床温随之趋于正常。

表 4 CFB 锅炉运行参数表

	数 据
锅炉效率/％	90.36
脱硫率/％	91
Ca/S	1.97
一次风率/％	71.85
燃料量/$kg·s^{-1}$	5.15
石灰石量/$t·h^{-1}$	2
炉膛出口 O_2 量/％	3.84

4.4 焦煤比对温度场的影响

图 5 为燃料中焦煤比对温度场的影响曲线图。当其它工况条件相同，燃料焦煤比由 1∶1 变为 3∶1 时，炉内温度场趋于均匀，炉内上、下温差变小。这

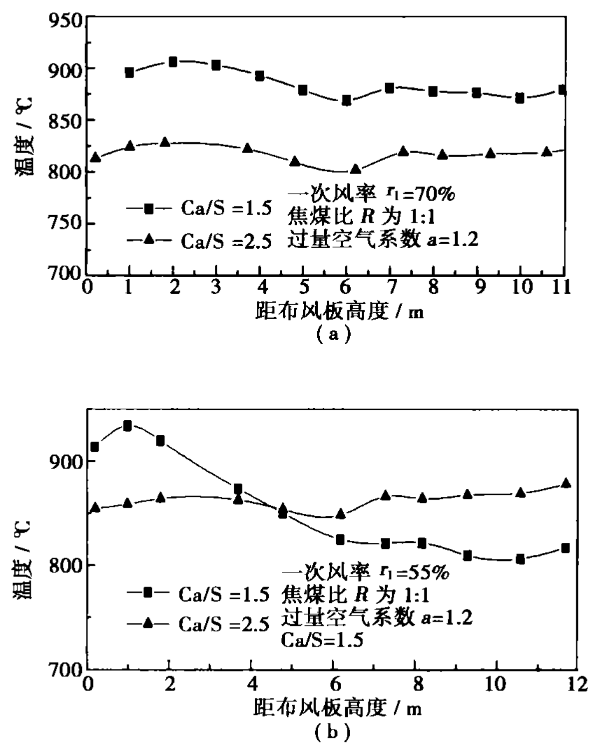


图 4　Ca/S 比对温度场的影响

是由于石油焦的粒径比煤要小, 挥发份含量也低, 当燃料中石油焦的含量增多, 密相区的燃烧份额将减少, 稀相区燃烧份额增多, 从而缩小了彼此的温度差异。

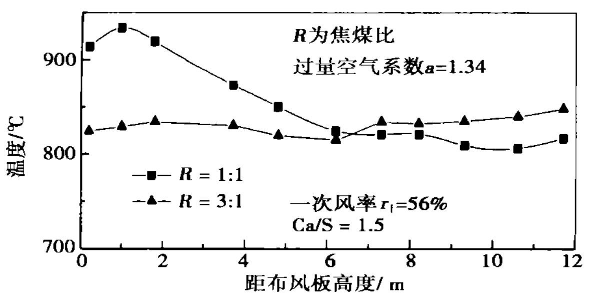


图 5　焦煤比对温度场的影响

对于石油焦与煤混烧, 最主要是要保证一定的物料循环量和密、稀相区的燃烧份额分布。对于纯焦燃烧, 积累的床层物料量偏少, 物料循环量也低, 造成炉内温度场不均匀。对于焦煤比为 3∶1 的混合燃料, 燃料粒径分布、物料循环量都达到了最佳值范围, 因此炉内温度场也趋于均匀。

4.5　燃料给料量对温度场的影响

燃料给料量对温度场的影响如图 6 所示。当给料螺旋转数由 520 r/min 降低到 450 r/min 时, 炉内平均温度由约 855 ℃降低到约 830 ℃。热输入率降低, 造成炉内温度降低。另外, 当总风量相同时, 减小给料量, 将增大过量空气系数, 对温度降低也有促进作用。

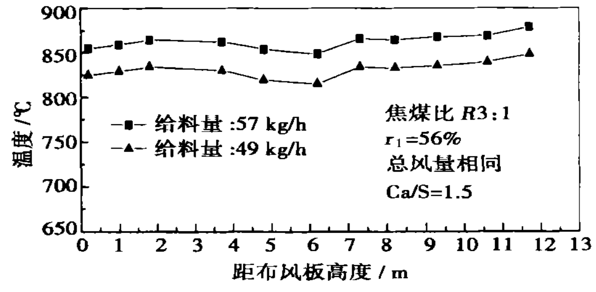


图 6　燃料给料量对温度场的影响

5　结　论

(1) 对于不同燃料掺混比, 随一次风率增大, 密相区温度降低, 炉膛温度更趋于均匀。

(2) 随过量空气系数增大, 密、稀相区温度降低。

(3) 随 Ca/S 比增大, 炉内平均温度降低。

(4) 当其它工况条件相同, 燃料焦煤比由 1∶1 变为 3∶1 时, 炉内温度场趋于均匀, 炉内上、下温差变小。

(5) 给料量减小, 炉内温度降低。

(6) 对于纯焦燃烧, 在无外加床料情况下密、稀相区温差很大, 燃烧份额分布、燃烧组织都不理想。

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To understand the formation mechanism of NO_X during a combustion process, tests were conducted over the temperature range of 873-1 673 K by selecting pyridine and pyrrole as nitrogen-containing model compounds. With the combined use of a Fourier transform infrared spectrometer (Ft-Ir) and a spectrophotometer the law of HCN and NH_3 escape during the pyrolysis of model compounds was experimentally investigated in an isothermal continuous-flow reactor. The investigation results indicate that HCN is the main nitrogen-containing product in the pyrolysis products of model compounds. The conversion rate of pyridine and pyrrole will increase with a rise in temperature. Under a same temperature the HCN formation rate of pyrrole is higher than that of pyridine and the NH_3 formation rate of pyrrole is higher than that of pyridine. **Key words**: coal combustion, nitrogen, model compound, Fourier transform infrared radiation analyzer

氧化钙添加剂对烟气中汞分布的影响＝**The Impact of CaO Additive on Mercury Distribution in Flue Gases** [刊,汉] / WANG Quan-hai, QIU Jian-rong, YANG Jian-feng, et al (National Key Laboratory of Coal Combustion under the Huazhong University of Science & Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 249~251.

Under the condition of one atmospheric pressure and within a temperature range of 273.15-1 273.15 K the impact of CaO and HCl formed during a combustion process on the morphology and distribution of trace element mercury was investigated through the use of an analytical method based on chemical thermodynamic-equilibrium. The results of the analysis indicate that elemental mercury is the main form of the mercury in the maximum temperature zone of coal combustion. With the reduction of temperature in flue gases the elemental mercury will undergo a chemical reaction, resulting in the formation of a bivalent mercury compound, which mainly assumes the form of $HgCl_2$(g). The results being forecast also show that an increase in chlorine elements can lead to an increased evaporation and emission of the mercury element. On the other hand, CaO(s) does not exercise a great influence on the behavior characteristics of mercury in the flue gases. There exists a relatively great difference between the results of chemical thermodynamic-equilibrium analysis and those of experiments. In spite of this, a comparison of the two sets of results still allows one to conclude that the CaO(s) has influenced the distribution characteristics of mercury element in the flue gases. This has been brought about mainly through a decrease in ash-particle surface area and/or a change in fly ash mineralogical and morphological features. **Key words**: coal, mercury, CaO, morphology

流化床部分煤气化实验研究＝**Experimental Study of Coal Partial Gasification in a Fluidized Bed** [刊,汉] / ZHOU Hong-cang, JIN Bao-sheng, ZHONG Zhao-ping, et al (Education Ministry Key Laboratory of Clean Coal Power Generation and Combustion Technology under the Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 252~255

On a small-sized coal partial-gasification test facility for a fluidized bed gasification tests of three kinds of coal were carried out under different operating conditions (namely, different coal feed rate, fluidized air flow rate and steam feed rate) with air and steam serving as gasifying agents. The results of the test show that the bed temperature decreases with an increase in coal feed rate and steam flow rate and also with a decrease in fluidized air flow rate. Within a certain range the CO content in gas will increase with an increase in coal feed rate, fluidized air flow rate and steam flow rate and also with a decrease in gasification degree. H_2 content in the gas will decrease with an increase in coal feed rate and gasification degree and also with a reduction in fluidized air flow rate and steam flow rate. CH_4 content will increase with an increase in coal feed rate, and will decrease with an increase in fluidized air flow rate, steam flow rate and gasification degree. Moreover, with a higher gasification degree the heating value of the generated gas will decrease. **Key words**: fluidized bed, coal partial gasification, experimental study

循环流化床中石油焦与煤混合燃烧温度场研究＝**A Study of the Temperature Profile Resulting from the Mixed Combustion of Petroleum Coke and Coal in a Circulating Fluidized Bed** [刊,汉] / WANG Wen-xuan, ZHANG Shou-yu, YUE Guang-xi (Department of Thermal Energy Engineering, Tsinghua University, Beijing, China, Post Code: 100084), ZHAO Chang-sui (Research Institute of Thermal Energy Engineering under the Southeastern University, Nan-

jing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy &Power. — 2004, 19(3). —256~259

As a byproduct of crude refining process petroleum coke features a low ash content, moderate volatility and a high heating value. It contains a sizable quantity of metallic elements, such as vanadium and nickel as well as sulfur and nitrogen. During the combustion of petroleum coke these elements can cause in-boiler corrosion and fouling. After a technical study it is found that the mixed combustion of petroleum coke and coal in a circulating fluidized bed represents an effective and environment-friendly approach for the utilization of and heat recovery from the petroleum coke. To verify the above fact a study concerning the temperature profile obtained in the course of mixed combustion of petroleum coke and coal was performed on a circulating fluidized bed hot-state test rig with a heat input of 0.5 MW. The impact of various factors and parameters on the temperature profile in a boiler furnace was investigated. They include the different blending ratios of petroleum coke and coal, different boiler operating parameters, such as primary-air flow rate, excess air factor, Ca/S ratio and coal feed rate, etc. **Key words**: circulating fluidized bed, petroleum coke, coal, combustion of blended fuels, temperature profile

水煤膏管内层流和过渡区的阻力特性＝**Resistance Characteristics of Coal-water Paste in a Pipe at the Laminar Flow and Transition Zones** [刊，汉] / LU ping (College of Power Engineering under the Nanjing Normal University, Nanjing, China, Post Code: 210042), ZHANG Ming-yao (Research Institute of Thermal Energy Engineering under the Southeastern University, Nanjing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy &Power. — 2004, 19(3). — 260~264

Based on the analysis of slip flow mechanism in a non-Newtonian fluid pipe the authors have come up with a method for determining the resistance losses of coal water paste through the calculation of a generalized Reynolds number Reg for the in-pipe flow of coal water paste. The results of an analysis indicate that the generalized Reynolds number is suitable not only for non-Newtonian fluid flow with slip being present in a pipe, but also suited for non-Newtonian and Newtonian fluid flow without a slip. Test results show that the critical Reynolds number of the steady flow of coal water paste in the pipe is approximately 2100. The formula for calculating resistance factors for laminar flow zones with the use of a generalized Reynolds number is similar to the simplified form for Newtonian fluid, namely, $\lambda=64/Reg$. The resistance loss at a transition zone can approximately satisfy Blasius equation, namely, $\lambda=0.316Reg^{-0.25}$. **Key words**: coal-water paste, generalized Reynolds number, resistance characteristics, slip phenomena

磁场抑制自然对流的能量涨落分析＝**Analysis of the Kinetic Energy Fluctuations of Magnetic Field-suppressed Natural Convection** [刊，汉] / ZHAO Liang-ju (Power Engineering Institute under the Chongqing University, Chongqing, China, Post Code: 400044), Daniel Henry, Hamda Benhadid (Laboratoire de Mecanique des Fluides et de Acoustique, Ecole Central de Lyon, France)//Journal of Engineering for Thermal Energy &Power. — 2004, 19(3). — 265~269

Bridgman method is often used for the fabrication of high-performance single crystals. During the melting of crystals the natural convection caused by a density difference will lead to a lowering of crystal quality. Through the use of an externally added magnetic field the natural convection was suppressed. By employing a spectral element method a numerical simulation was performed of the three-dimensional non-steady-state natural convection of a gallium melt. As a result, obtained was (when $Pr = 0.019$) a time-dependent variation of pulsating kinetic energy fluctuations caused by pulsating kinetic energy in the absence of an externally added magnetic field, transverse and longitudinal magnetic fields as well as by the convection, viscous dissipation and floating force action. Meanwhile, the various components representing energy fluctuations caused by the convection, which plays a major role in pulsation kinetic energy variation, undergo a further analysis. The convection is a key factor leading to fluctuations of pulsation kinetic energy, while the horizontal speed gradient constitutes a main constituent part of the convection item. **Key words**: magnetic field, natural convection, spectral finite element simulation, pulsating kinetic energy fluctuations